**Title :** Routing and scheduling algorithms to guarantee low latency and no jitter in 5G and beyond architectures

Current mobile network architecture consist in distributed radio access networks. The evolutions proposed in next generations aim centralized radio network architectures (C-RAN) to reduce consumption costs and power at the base stations. These C-RAN architectures include simplified base stations at each antenna (Remote Radio Heads: RRH) and central processing units (baseband unit: BBU) located in the cloud. Thus, this type of architecture confronts the problem of mastering the latency in the transfer process. Low latency is considered critical for the 5G, in particular for the deployment of C-RAN approach (allowing time constraints like HARQ to be fulfilled over non dedicated networks), or to reach E2E expected latency from 1 to 10ms (depending on targeted services). One specificity in the C-RAN context is not only the latency constraint, but also th periodicity of the data transfer between RRH and BBU. New scheduling and routing paradigms and new technologies have to be considered to guarantee delay constrained periodic data transfers. Dynamical optical bypass and dynamical management of the emission should be considered to guarantee latency constraints.

Thus, this PHD subject targets new scheduling and routing paradigms to solve this periodic and delay constrained data transfer. Indeed, one of the most promising approaches relies to the concept of Deterministic Networking (DN) such that one get rid of statistical multiplexing. The traditional queue managements are replaced by time based forwarding. Solutions for Deterministic Networking are under standardization in IEEE 802.1 TSN group, as well at IETF DetNet working group. To make DN working over a network composed of several nodes, it is needed to manage the time at which the packets of deterministic paths are crossing each nodes.

A first algorithmic modelisation have been proposed and analyzed in collaboration between Nokia Bell Labs France and DAVID laboratory. We consider a graph modeling the network topology, and a set of routes from source nodes (modeling data-centers) to destination nodes (modeling base stations). The purpose of our work is to find a routing scheme allowing to periodically send a packet to each base station without congestion conflicts between all such packets, while insuring a minimum latency. Given maximum values of the data transfer time (about 3 ms included the computation time in the cloud in the C-RAN context) and of the periodicity (about 1 ms in the same context), in a slotted time model, the aim is here to minimize the duration of the period, with a constraint of the maximum length of routes to be selected. Even if the selected set of routes is given this optimization problem has been shown to be NP-complete. Several graph colorings have been introduced to model allocation of frequencies[1], bandwidths[2] or routes[3] in a network or train schedules[4]. Unfortunately, they do not take into account the periodicity and the associated problems are NP-complete. The only model which incorporates some periodicity is the circular coloring[5,6,7] but is not expressive enough to capture our problem.

We plan to study several topologies of networks: the star for which several results are already available, the cycle representing an optical ring and the acyclic graph representing a general meshed network. We will try to characterize the restrictions of the previous topologies which make our problem polynomial time solvable or approximable. In particular, the time to transmit a packet seems to be large with regards to the size of a route. We hope to use this property to come up with new efficient algorithms.

To do that we will try to use ideas from scheduling and graph coloration for similar problems, by taking into account the periodicity and also the problem to optimize over the way from RRH to BBU and back simultaneously. In particular, we are interested scheduling problems which minimize maximum lateness, such as [8], are interesting to us.

Another problem will be to enrich our modelisation to make it more general, by allowing different bandwidths on the links or to allow to cut the packets into pieces.

In this context, the study program of this project consists in :

1. Given a routing in a network connecting various RRH and BBU, analyzing theoretically the problem of defining a periodic scheduling (complexity, approximability, particular cases) and proposing efficient heuristic algorithms to solve it ;
2. Proposing some new routing algorithms to define the set of paths best suited to the resolution of the previous scheduling problem ;
3. Defining the specificity of the instances corresponding to the C-RAN context (network topologies, time, router technologies, functionalities) ;
4. Benchmarking the proposed algorithms through simulation on the defined instances in comparison with existing architectural solutions ;
5. Proposing solutions for an efficient coordination between computed scheduling and computation elements ;
6. Defining methods, procedures and tools needed to perform computed scheduling ; integrating these procedures into operation & orchestration framework used for SDN.
7. Demonstrating feasibility of the solutions proposed in the context of the 5G and beyond, through simulation and prototype.

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